(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
18 January 2001 (18.01.2001)

PCT

(10) International Publication Number
WO 01/04999 A1

(51) International Patent Classification[7]: H01S 3/00

(21) International Application Number: PCT/IL00/00401

(22) International Filing Date: 6 July 2000 (06.07.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/142,677 7 July 1999 (07.07.1999) US

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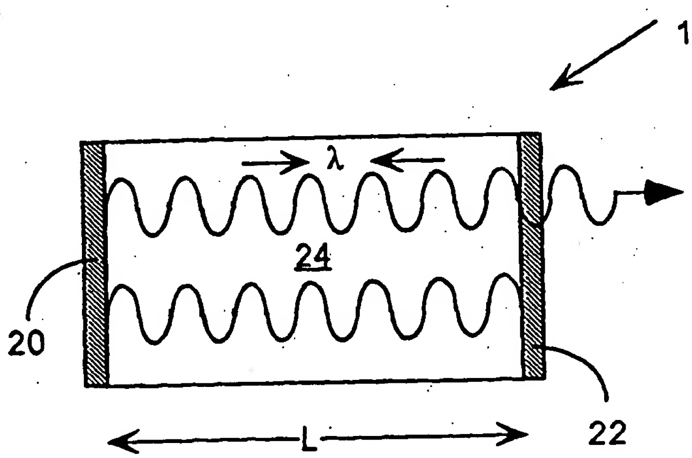
(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *With international search report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: LASER WAVELENGTH STABILIZATION



(57) Abstract: Apparatus f r stabilizing an output wavelength of a laser assembly (80), including a plurality of optical elements (88, 92, 97, 96) coupled together so as to form a laser cavity resonating in a single mode dependent upon an optical length of the cavity, and an optical length changer (86) which varies an optical length of at least one of the optical elements so as to vary accordingly the optical length of the cavity. The apparatus further includes a detector (91) which monitors the output of the laser assembly responsive to the variation in the optical length of the at least one of the optical elements. There is also included a stabilizer (93) which

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Fig. 2 is a graph of intensity I vs. wavelength λ illustrating cavity modes for system 18, as is known in the art. A curve 30 represents an overall gain of medium 24 in system 18. Peaks 32A and 32B, with separation $\Delta\lambda$, show the cavity modes present in system 18, each node corresponding to a different value of m. As is evident from Fig. 2, there are many possible cavity modes for system 18.

Optical communications within fiber optic links require that the laser carrier have as small a frequency spread as possible, particularly when multiple wavelengths are to be multiplexed on a single fiber. Thus, for efficient communication only one cavity mode should be used, and optimally the frequency spread within the mode should be minimized. Typically, methods for stabilizing the frequency of the laser include utilizing distributed feedback (DFB) lasers and/or distributed Bragg reflectors (DBR). DFB lasers have a frequency-selection grating built into the laser chip, the grating being physically congruent with the gain medium. The grating in a DBR laser is external to the gain medium. The gratings in DFB and DBR lasers are part of the semiconductor material, which is unstable. DFB and DBR lasers are therefore typically externally stabilized utilizing an external wavelength reference in order to achieve good stability.

Fig. 3 shows the effect of adding a tuning element such as a fiber grating to system 18, as is known in the art. A curve 34 shows the resonance curve of the fiber grating, which has a bandwidth $\Delta\lambda_G$ of the same order as $\Delta\lambda$, the separation between the longitudinal cavity modes. If the grating is optically coupled to system 18, then mode 32A is present, and other modes such as mode 32B, are suppressed.

Fig. 4 is a schematic diagram showing a gain medium 38 coupled to a fiber grating 50, as is known in the art. Gain medium 38 is formed from a semiconducting gain element 44 having a laser gain region 42. Light from region 42 exits from a facet 56 of region 42 to a medium 46, and traverses medium 46 so that a lens 48 collects the light into a fiber optic 52. Fiber grating 50 is mounted in fiber optic 52, which grating reflects light corresponding to curve 34 of Fig. 3 back to region 42. The mirrors of the laser cavity comprise a rear mirror which in this example is a back facet 57 of the semiconductor gain element, and an output coupling mirror which in this example is the fiber grating. The rear and output coupling mirrors could also be reversed. In the reversed configuration the rear mirror would be the fiber grating and the output coupling mirror would be back facet 57 of the semiconductor gain element. In the reversed configuration the detector would preferably be positioned behind the fiber grating. It is desirable to eliminate parasitic reflections due to surfaces and interfaces internal to the cavity. To eliminate parasitic reflection from the facet of the

mode 32A.

U. S. patent 4,786,132 to Gordon, whose disclosure is incorporated herein by reference, describes a semiconductor laser diode coupled to a single mode optical fiber. The fiber comprises a built-in Bragg reflector grating which reflects of the order of 50% of the light from the laser back to the laser. The reflected light provides feedback to the laser so that the laser produces a single frequency output.

U. S. patent 5,077,816 to Glomb et al., whose disclosure is incorporated herein by reference, describes a narrowband laser source, a portion of the light from which is supplied to a resonant grating region in a fiberoptic, external to the laser. The current through the laser is dithered, causing the frequency of the laser to dither. The corresponding dithered light intensity transmitted by the grating is used in order to adjust the current through the laser so as to maintain the frequency of the laser at the resonant frequency of the grating.

U. S. patent 5,706,301 to Lagerstrom, whose disclosure is incorporated herein by reference, shows a laser control system which uses a fiber optic grating as a resonant control element. A difference in light intensity between laser light passing through the grating, and light which does not pass through the grating is measured, and the difference is used in order to vary the temperature of a laser generating the light, so as to maintain the frequency of the laser at the resonant frequency of the grating.

the laser and the insulating element. The insulating element has the effect of ensuring that a maximal temperature increase in the laser is attained for a given input electrical power to the heating element. Thus the heating element may be used to modulate the temperature and to change the mean temperature of the laser (or of one or more other elements within the laser assembly) in a controlled manner, and thus to modulate and change the mean value of the optical length of the one or more elements.

In some preferred embodiments of the present invention, at least some of the elements comprising the laser assembly are coupled to a thermoelectric cooler, which enables the temperature of the coupled elements to be changed. Changing the temperature of the fiber grating enables its resonant wavelength to be adjusted in a controlled manner.

There is therefore provided, according to a preferred embodiment of the present invention, apparatus for stabilizing an output wavelength of a laser assembly, including:

a plurality of optical elements coupled together so as to form a laser cavity resonating in a single mode dependent upon an optical length of the cavity;

an optical length changer which varies an optical length of at least one of the optical elements so as to vary accordingly the optical length of the cavity;

a detector which monitors the output of the laser assembly responsive to the variation in the optical length of the at least one of the optical elements; and

a stabilizer which responsive to the measured output from the detector suppli s a control signal to the optical length changer to control an optical length of at least one of the optical elements, so that the cavity resonates stably at the output wavelength in the single mode.

Preferably, the optical length changer includes a heating element which varies a temperature of at least one of the optical elements, thereby varying the optical length of the at least one of the optical elements.

Preferably, the heating element includes an electric heating element, which is supplied by a direct current component and an alternating current component in order to alter and modulate a mean temperature of at least one of the optical components.

Further preferably, the heating element dissipates a modulated power having a peak value less than or equal to about 200 mW.

Preferably, the heating element includes a heat insulating element, which selectively directs heat to the at least one of the optical elements.

Preferably, the heat insulating element includes silicon dioxide.

Preferably, the plurality of optical elements includes a semiconductor gain region and

at least one of the plurality of elements.

Preferably, adjusting the effective cavity length includes adjusting a temperature of at least one of the plurality of elements.

Preferably, adjusting the effective cavity length includes adjusting at least one of the effective optical lengths.

Preferably, modulating the at least one of the effective optical lengths includes measuring a phase of a modulation of the effective optical length, monitoring the radiation output includes monitoring a radiation output phase and evaluating a comparison of the phase of the modulation of the effective optical length with the radiation output phase, and adjusting the effective cavity length includes adjusting at least one of the effective optical lengths responsive to the comparison.

Preferably, adjusting the effective cavity length includes adjusting the length responsive to the monitored radiation output substantially without reliance on an external wavelength reference.

Preferably, the method includes varying a resonant wavelength of at least one of the plurality of elements responsive to the single mode of the cavity.

There is further provided, according to a preferred embodiment of the present invention, laser apparatus, including:

a plurality of optical elements coupled together so as to form a laser cavity resonating in a single mode, one of the plurality of elements having a tunable resonant wavelength; and

a thermal transfer element which is adapted to vary a temperature of the one of th plurality of elements so as to tune the resonant wavelength to correspond with the single mode.

Preferably, the one of the plurality of elements includes a fiber grating.

There is further provided, according to a preferred embodiment of the present invention, laser apparatus, including:

a plurality of optical elements coupled together so as to form a laser cavity resonating in a single mode, a first one of the plurality of elements having a resonant wavelength; and

a thermal transfer element which is adapted to vary a temperature of at least a second one of the plurality of elements, so as to tune the single mode to correspond with the resonant wavelength.

Preferably, the first one of the plurality of elements includes a fiber grating.

There is further provided, according to a preferred embodiment of the present invention, a method for generating a laser output, including:

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic diagram showing operation of a lasing system, as is known in the art;

Fig. 2 is a graph of intensity vs. wavelength, illustrating cavity modes for the system of Fig. 1, as is known in the art;

Fig. 3 shows the effect of adding a spectrally selective element such as a fiber grating to the system of Fig. 1, as is known in the art;

Fig. 4 is a schematic diagram showing a semiconductor gain medium coupled to a fiber grating forming a fiber grating laser (FGL), as is known in the art;

Fig. 5 is a schematic illustration showing a stabilized fiber grating laser system, according to a preferred embodiment of the present invention;

Fig. 6 is a schematic perspective diagram of a diode assembly comprised in the system of Fig. 5, according to a preferred embodiment of the present invention;

Figs. 7A, 7B, and 7C are temperature vs. time graphs for different points in the diode assembly shown in Fig. 6 for different thicknesses of a heat insulator, according to a preferred embodiment of the present invention;

Fig. 8 is a graph showing schematically the effect of modulation of an optical length on the intensity of radiation emitted by the system of Fig. 5, according to a preferred embodiment of the present invention; and

Fig. 9 is a schematic diagram of a stabilized fiber grating laser system, according to an alternative preferred embodiment of the present invention.

$n_l \cdot L_l$ corresponds to an optical length of region 88;
$n_0 \cdot L_0$ corresponds to an optical length of region 92;
$n_f \cdot L_f$ corresponds to an optical length of region 97; and
$n_g \cdot L_{gef}$ corresponds to an optical length of region 96.

As described herein, the wavelength of system 80 is stabilized to the tuned wavelength of the peak of the resonance curve of the fiber grating, λ_f, by adjusting the effective length L_{eff}.

In order to stabilize system 80, a wavelength stabilizer 93 supplies an electric current to heating element 86. Most preferably, the current comprises a direct current component and an alternating current component, the levels of which components are separately adjustable by stabilizer 93. Preferably, the frequency of the alternating current is set to be less than about 5 kHz. The current supplied by stabilizer 93 has the effect of both raising the mean temperature of diode 81, and of varying the temperature about the mean temperature with a frequency equal to that of the applied alternating current. As described in more detail below, heating element 86 and insulator 84 act as an optical length changer by changing the temperature of diode 81. The changes in temperature alter the optical length of system 80, which in turn changes the intensity of the laser radiation emitted by region 88 of diode 81, and the changes in emitted intensity are used in a feedback loop to stabilize the wavelength emitted by the system.

A portion of the laser radiation from region 88 is captured by a detector 91. Detector 91 is preferably any industry-standard optical radiation detector, for example comprising InGaAs, which is able to measure the intensity of the radiation incident on the detector. Changes of radiation intensity, as measured by detector 91, are fed back to stabilizer 93, and the measured changes are used by the stabilizer to vary the level of the direct current supplied to element 86. The level of the direct current is adjusted by stabilizer 93 in a feedback loop so as to maintain the wavelength of system 80 at a substantially fixed value determined by the resonance curve of the fiber grating.

Fig. 6 is a schematic perspective diagram of diode assembly 81, showing different positions in the assembly, according to a preferred embodiment of the present invention. Figs. 7A, 7B, and 7C are temperature vs. time graphs for the positions shown in Fig. 6 using different thicknesses of heating insulator 84, according to a preferred embodiment of the present invention. Electrical contact pad 87 to the diode 81 and electrical insulation layer 95 between the contact pad and heating element 86 are not shown since they only have a

positions 110, 108, and 106. Graph B1 corresponds to results obtained for position 104, and also substantially to results for position 102. The results shown by graphs B5, B4, and B3 are respectively substantially as described above for graphs A5, A4, and A3. Graph B1 shows that at positions 102 and 104, the mean temperature is 24°C and there is a peak-peak temperature modulation of 0.75°C, so that these mean and peak-peak values correspond to the values for region 88 when a 1 μm insulator is present.

Graphs C5, C4, and C3 (Fig 7C) correspond respectively to results obtained for positions 110, 108, and 106. Graph C1 corresponds to results obtained for position 104 and also substantially to results for position 102. The results shown by graphs C5, C4, and C3 are respectively substantially as described above for graphs A5, A4, and A3. Graph C1 shows that at positions 102 and 104, the mean temperature is 25.25°C and there is a peak-peak temperature modulation of 1.25°C, so that these mean and peak-peak values correspond to the values for region 88 when a 2 μm insulator is present.

Comparison of graphs A3, B1, and C1, shows that as the thickness of insulator 84 is increased from 0 μm to 1 μm to 2 μm, the peak-peak temperature modulation of semiconductor regions 90 increases from 0.15°C to 0.75°C to 1.25°C, and the mean temperature increases from 22.5°C to 24°C to 25.25°C. Thus, when insulator 84 has a thickness of 2 μm, there is an effective gain of temperature modulation equal to 1.25/0.15 i.e., a gain of approximately 8. When insulator 84 has a thickness of 1 μm, the effective gain is 0.75/0.15 = 5.

Modulating the temperature of regions 90 correspondingly modulates the physical length L_l of diode 81, due to thermal expansion and contraction of the diode, and also modulates the refractive index n_l of the diode. Thus the optical length L_{eff} of assembly 81 is modulated in phase with the modulation in temperature.

Fig. 8 is a schematic graph showing the effect of modulation of optical length L_{eff} on the intensity of radiation emitted by system 80, according to a preferred embodiment of the present invention. A graph 116 represents the graph of intensity I vs. wavelength λ for a longitudinal cavity mode at which system 80 is lasing, wherein the resonant wavelength of the mode is λ_L, and wherein the effective length of system 80 is $L_{eff(L)}$. At a point 118 on graph 116 system 80 has an effective length $L_{eff(L-)}$, less than $L_{eff(L)}$, and the wavelength produced by the assembly is λ_{L-}, less than λ_L. At a point 112 on graph 116 system 80 has an effective length $L_{eff(L+)}$, greater than $L_{eff(L)}$, and the wavelength produced by the system is λ_{L+}, greater than λ_L.

substrate, or laser, are of different materials.

Signals from detector 91, responsive to the modulation in radiation intensity, are compared in stabilizer 93 to the alternating current signals applied to heater 86. Most preferably, the phases of the detector signals and the alternating current are compared to determine a position on a resonant curve of assembly 80 where the assembly is operating, as described above with reference to Fig. 8. Alternatively or additionally, other measures are used to determine the position on the resonant curve of assembly 80. For example, one measure is the slope of the change of the laser intensity due to a change in wavelength, caused by an effective length change due to a temperature change. A positive slope is associated with a mean length $L_{eff(L-)}$, corresponding to system 80 operating at wavelength λ_{L-}. A negative slope is associated with a mean length $L_{eff(L+)}$, corresponding to system 80 operating at wavelength λ_{L+}. A substantially zero slope is associated with mean length $L_{eff(L)}$, corresponding to system 80 operating at wavelength λ_L which is the peak wavelength of the resonance curve of the fiber grating. Stabilizer 93 uses the determined position in order to set a level of the direct current applied to heater 86, thereby altering the mean temperature of diode 81, so as to maintain assembly 80 resonating at a substantially constant resonating wavelength λ_L.

Fig. 9 is a schematic diagram of a stabilized fiber grating laser system 150, according to an alternative preferred embodiment of the present invention. Apart from the differences described hereinbelow, the operation of assembly 150 is generally similar to that of assembly 80, so that elements indicated by the same reference numerals in both assembly 150 and assembly 80 are generally identical in construction and operation. Substrate 82 is mounted on a thermoelectric cooler 120, such as a model SP1020 produced by Marlow Industries, Inc., of Dallas, Texas, although any other standard or custom-built thermoelectric cooler may be used. Cooler 120 is a thermal transfer element which is generally utilized to control the mean temperature of lasers of different varieties and can also be used for the same purpose in embodiments of the present invention. As is known in the art, the mean temperature of a laser is affected by intrinsic effects like laser power dissipation or extrinsic effects like environmental effects. Cooler 120 is preferably powered by a power source external to assembly 150. Alternatively cooler 120 is powered by a power source internal to assembly 150, for example stabilizer 93 may act as a power source.

Cooler 120 can be used to reduce the mean temperature rise of diode 81 caused by modulation of element 86, required to produce a modulation of the effective length. Most preferably, cooler 120 is operated so as to allow insulator 84 to be thicker than in system 80,

combinations and subcombinations of the various features described hereinabove, as well as variations and modifications thereof which would occur to persons skilled in the art upon reading the foregoing description and which are not disclosed in the prior art.

9. Apparatus according to claim 8, wherein the at least one of the optical elements whose length is varied by the optical length changer comprises the semiconductor gain region.

10. Apparatus according to claim 8, wherein the plurality of optical elements comprises a medium optically coupling the semiconductor gain region and the fiber grating, and wherein the at least one of the optical elements whose length is varied by the optical length changer comprises the medium.

11. Apparatus according to claim 8, wherein the optical length of the cavity is varied to substantially lock the single mode of the cavity to the resonant wavelength.

12. Apparatus according to claim 8, wherein the optical length changer varies the optical length of the at least one of the optical elements so as to correspond to the resonant wavelength.

13. Apparatus according to claim 1, and comprising a thermal transfer element which varies a temperature of at least one of the optical elements, thereby varying the optical length of the cavity.

14. Apparatus according to claim 13, wherein the thermal transfer element comprises a cooling element, which is thermally coupled to the laser assembly and which extracts heat from the laser assembly so as to reduce an overall temperature of at least one of the plurality of optical elements.

15. Apparatus according to claim 14, wherein the cooling element is operated by the stabilizer, and wherein the cooling element extracts heat from the laser assembly responsive to the measured output from the detector.

16. A method for stabilizing a laser assembly, the assembly comprising a plurality of elements each having a respective effective optical length, the plurality of elements forming a cavity resonating at a lasing wavelength in a single mode and having an effective cavity length, the method comprising:

modulating at least one of the effective optical lengths;

monitoring a radiation output of the assembly responsive to the modulation; and

adjusting the effective cavity length responsive to the output and to the modulation, so as to maintain the cavity resonating at the wavelength in the single mode.

17. A method according to claim 16, wherein modulating the at least one of the effective lengths comprises modulating a temperature of at least one of the plurality of elements.

27. Apparatus according to claim 26, wherein the one of the plurality of elements comprises a fiber grating.

28. Laser apparatus, comprising:

a plurality of optical elements coupled together so as to form a laser cavity resonating in a single mode, a first one of the plurality of elements having a resonant wavelength; and

a thermal transfer element which is adapted to vary a temperature of at least a second one of the plurality of elements, so as to tune the single mode to correspond with the resonant wavelength.

29. Apparatus according to claim 28, wherein the first one of the plurality of elements comprises a fiber grating.

30. A method for generating a laser output, comprising:

coupling a plurality of optical elements together so as to form a laser cavity resonating in a single mode, one of the plurality of elements having a tunable resonant wavelength; and

varying a temperature of the one of the plurality of elements so as to tune the resonant wavelength to correspond with the single mode.

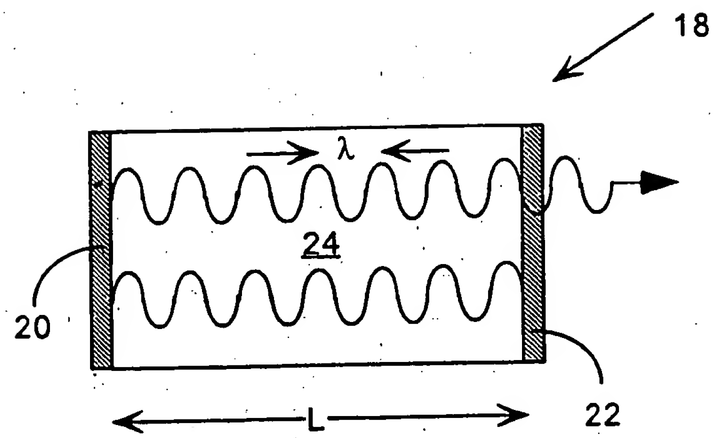
31. A method according to claim 30, wherein the one of the plurality of elements comprises a fiber grating.

32. A method for generating a laser output, comprising:

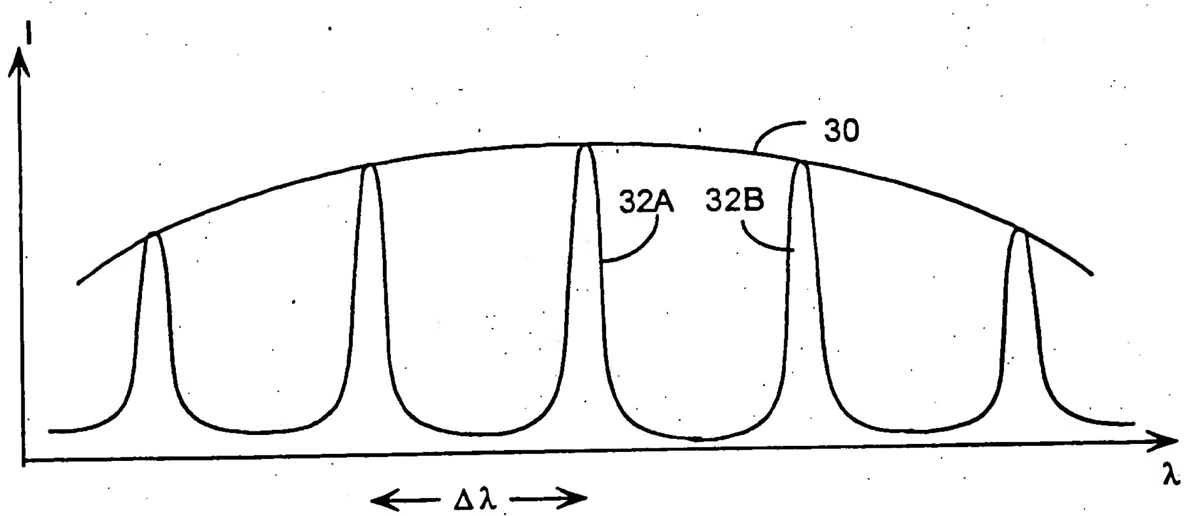
a plurality of optical elements coupled together so as to form a laser cavity resonating in a single mode, a first one of the plurality of elements having a resonant wavelength; and

a thermal transfer element which is adapted to vary a temperature of at least a second one of the plurality of elements, so as to tune the single mode to correspond with the resonant wavelength.

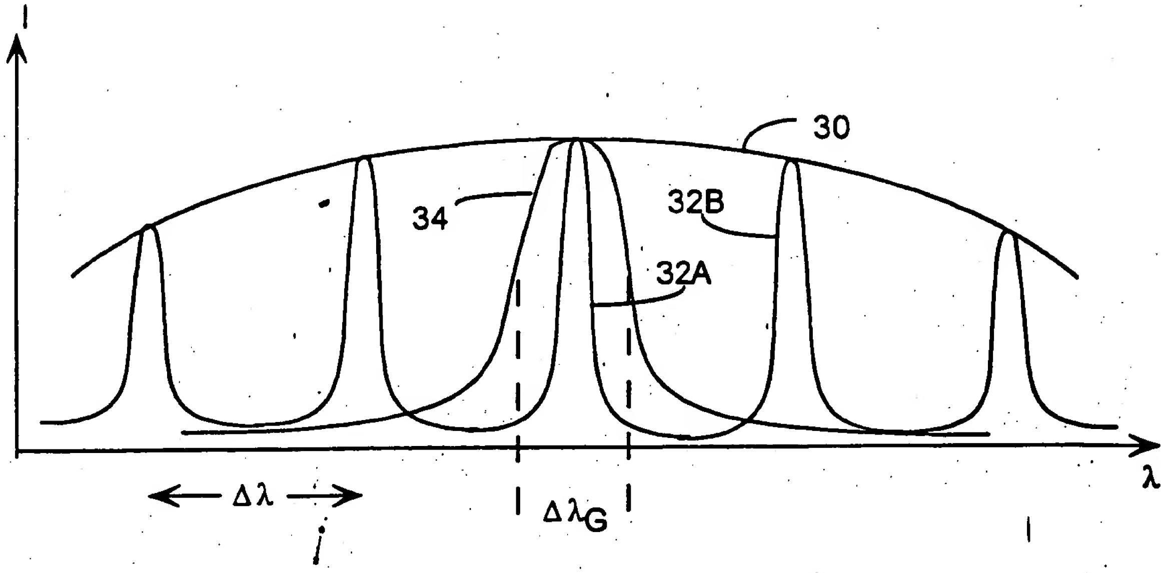
33. A method according to claim 32, wherein the first one of the plurality of elements comprises a fiber grating.



Prior Art
FIG. 1

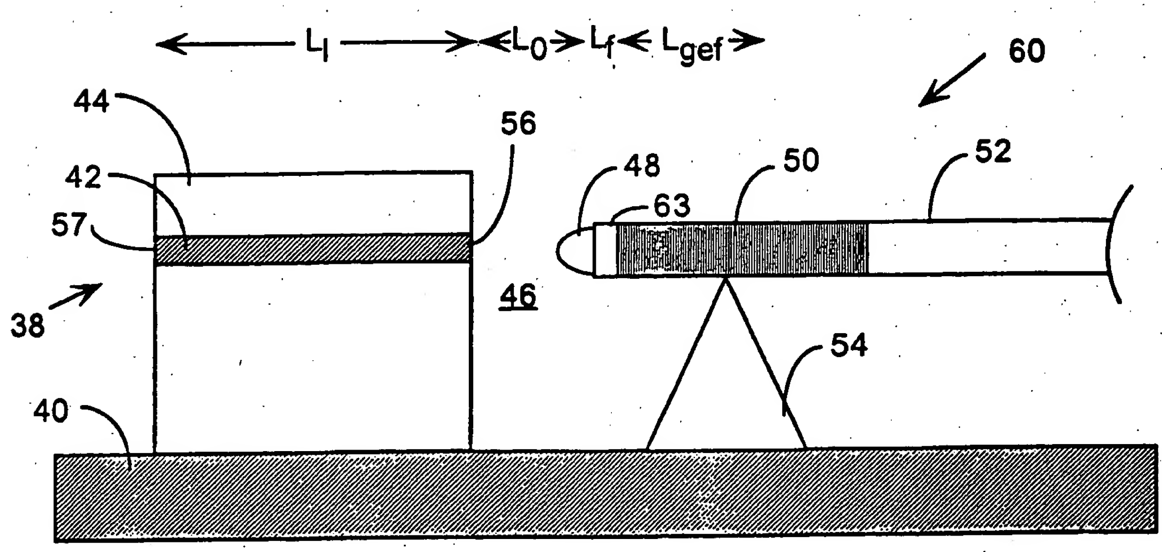


Prior Art
FIG. 2



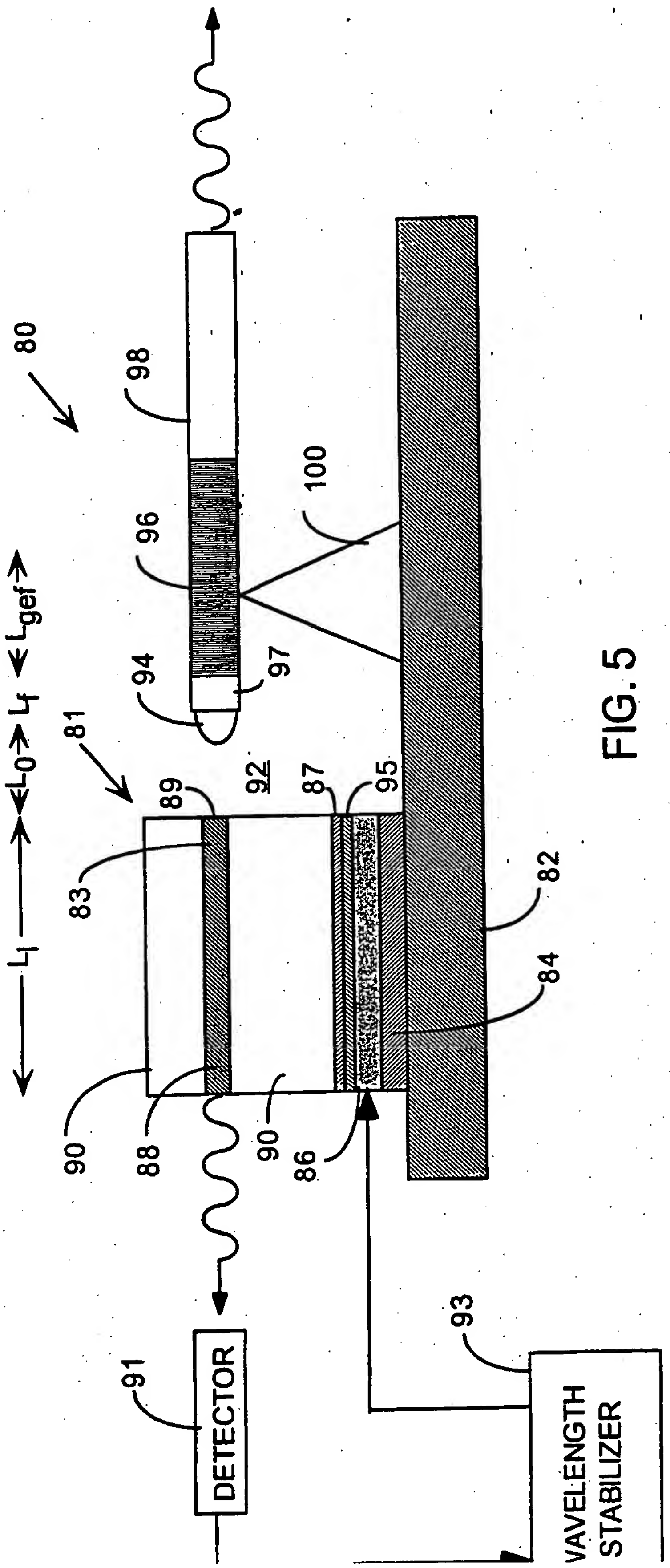
Prior Art

FIG. 3



Prior Art

FIG. 4


80
98
100
96
94
97
L_1
L_0
L_f
L_{gef}
81
89
92
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83
82
84
90
88
90
86
93
91
DETECTOR
VAVELENGTH
STABILIZER

FIG. 5

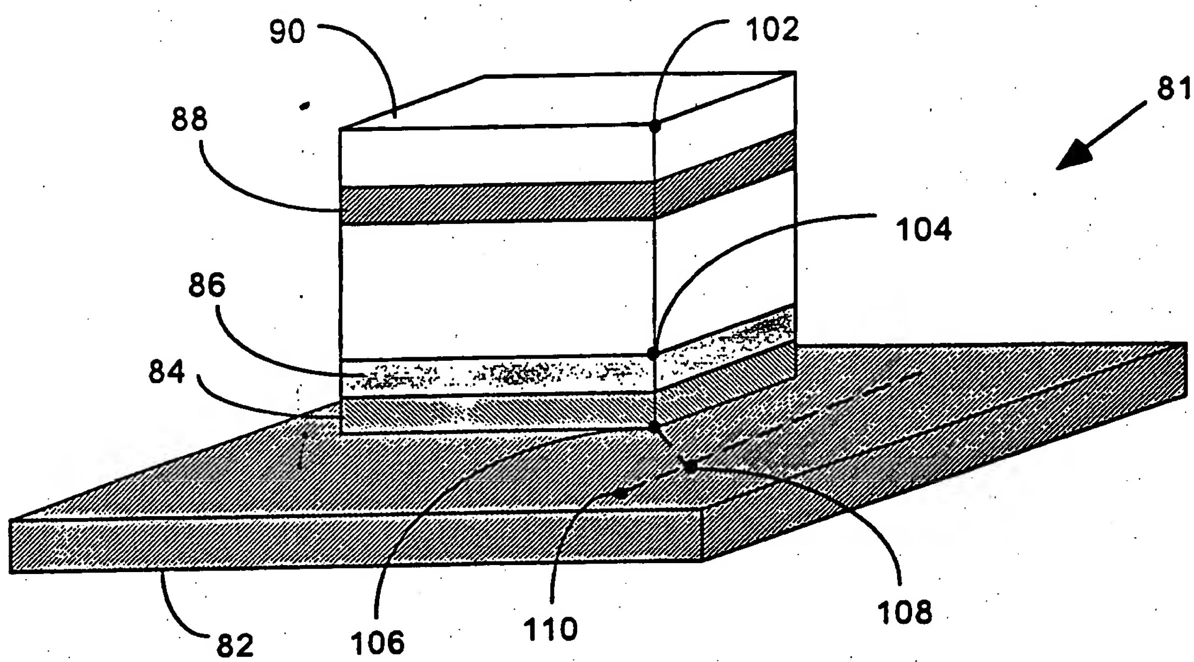
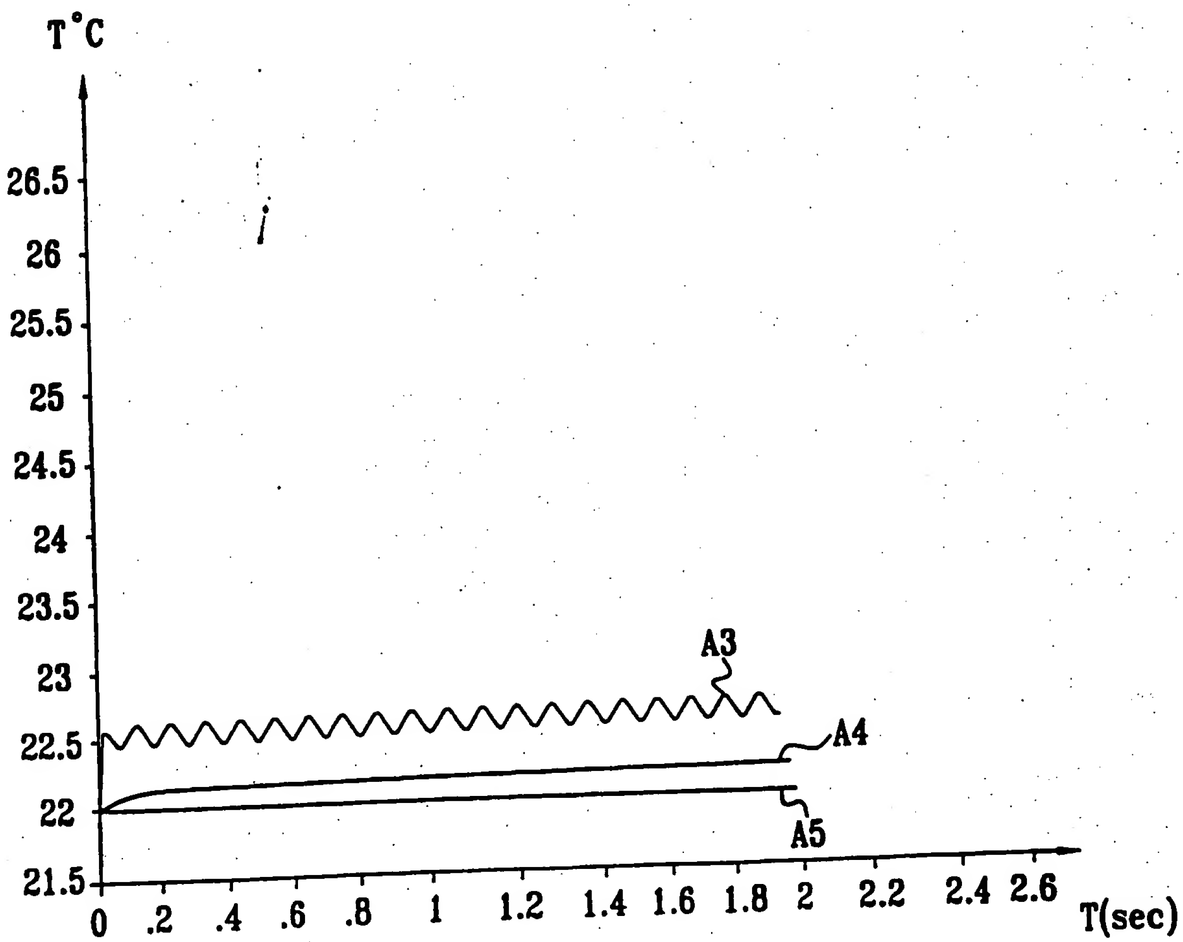


FIG. 6

FIG. 7A


T°C
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26
25.5
25
24.5
24
23.5
23
22.5
22
21.5
A3
A4
A5
0
.2
.4
.6
.8
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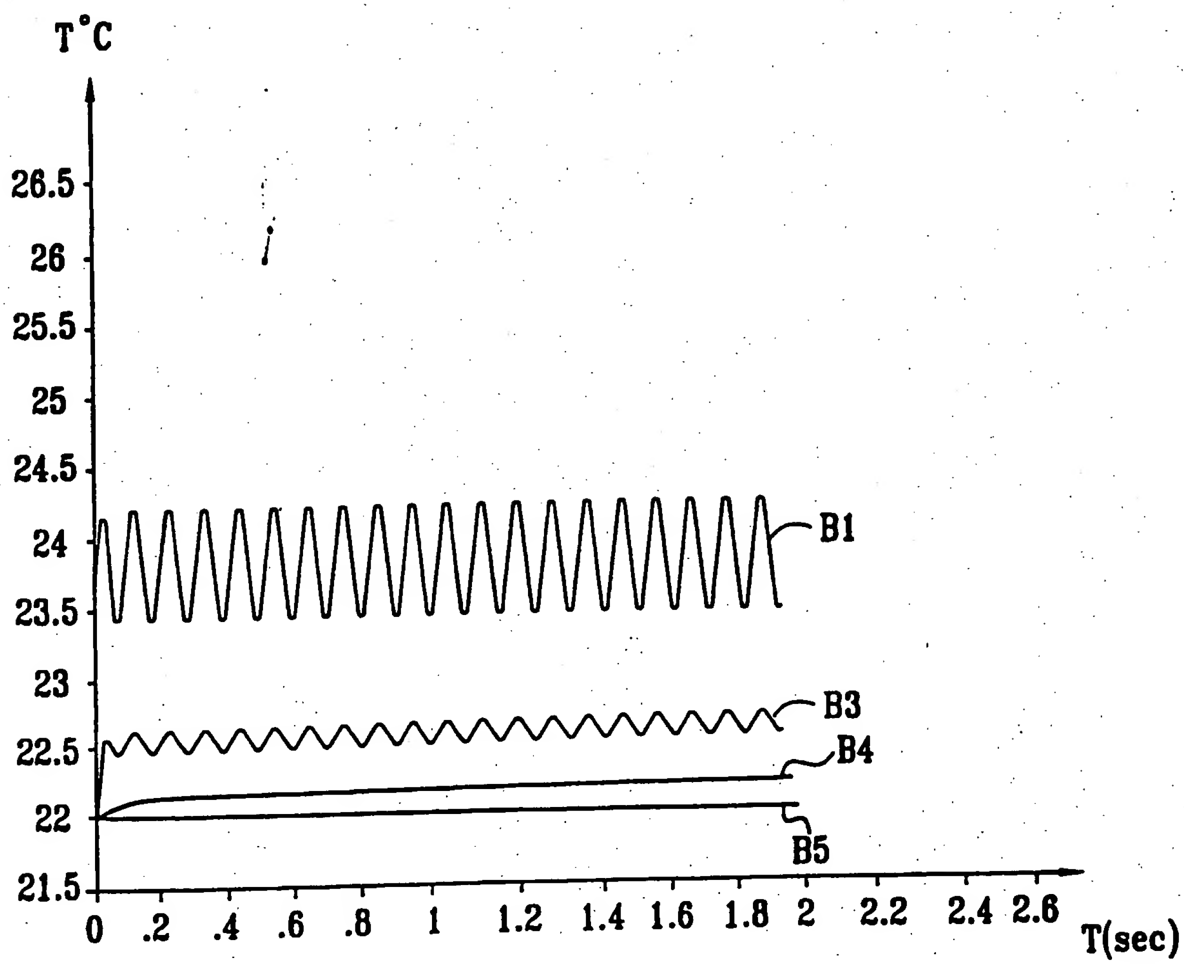
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
T(sec)

FIG. 7B


T°C
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22
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0
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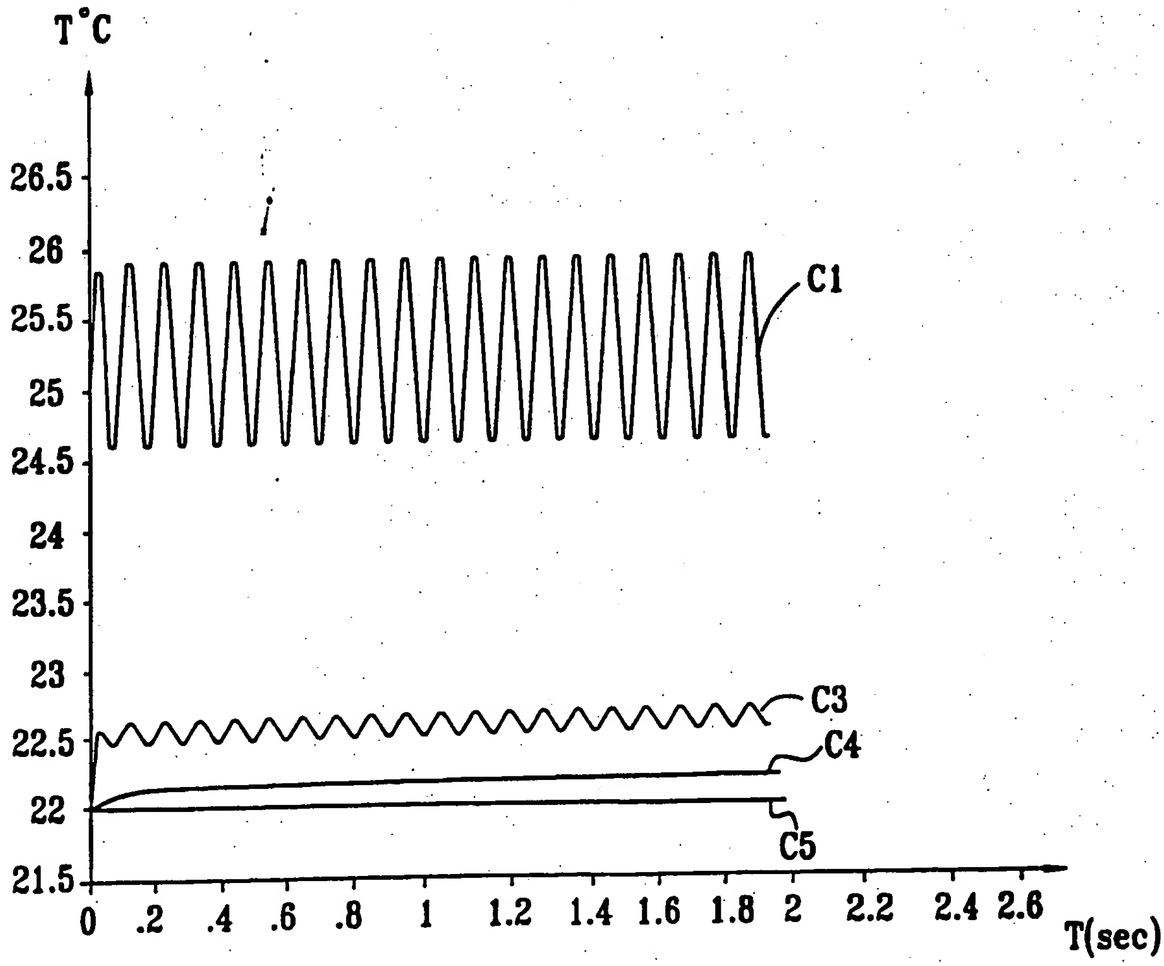
.6
.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
T(sec)
B1
B3
B4
B5

FIG. 7C


T°C
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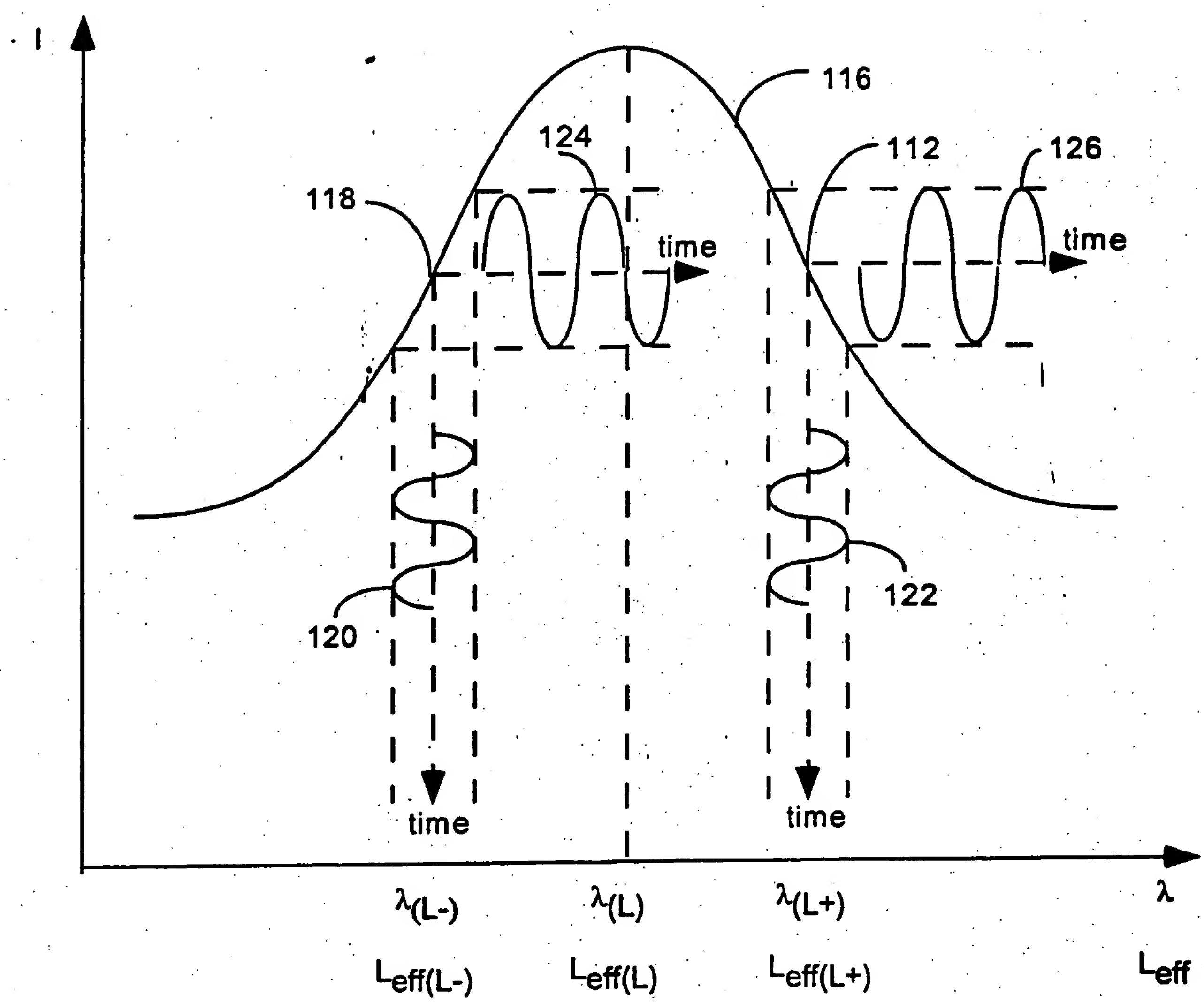
C1
C3
C4
C5


I
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118
time
time
120
122
time
time
λ
λ(L-)
λ(L)
λ(L+)
Leff(L-)
Leff(L)
Leff(L+)
Leff

FIG. 8

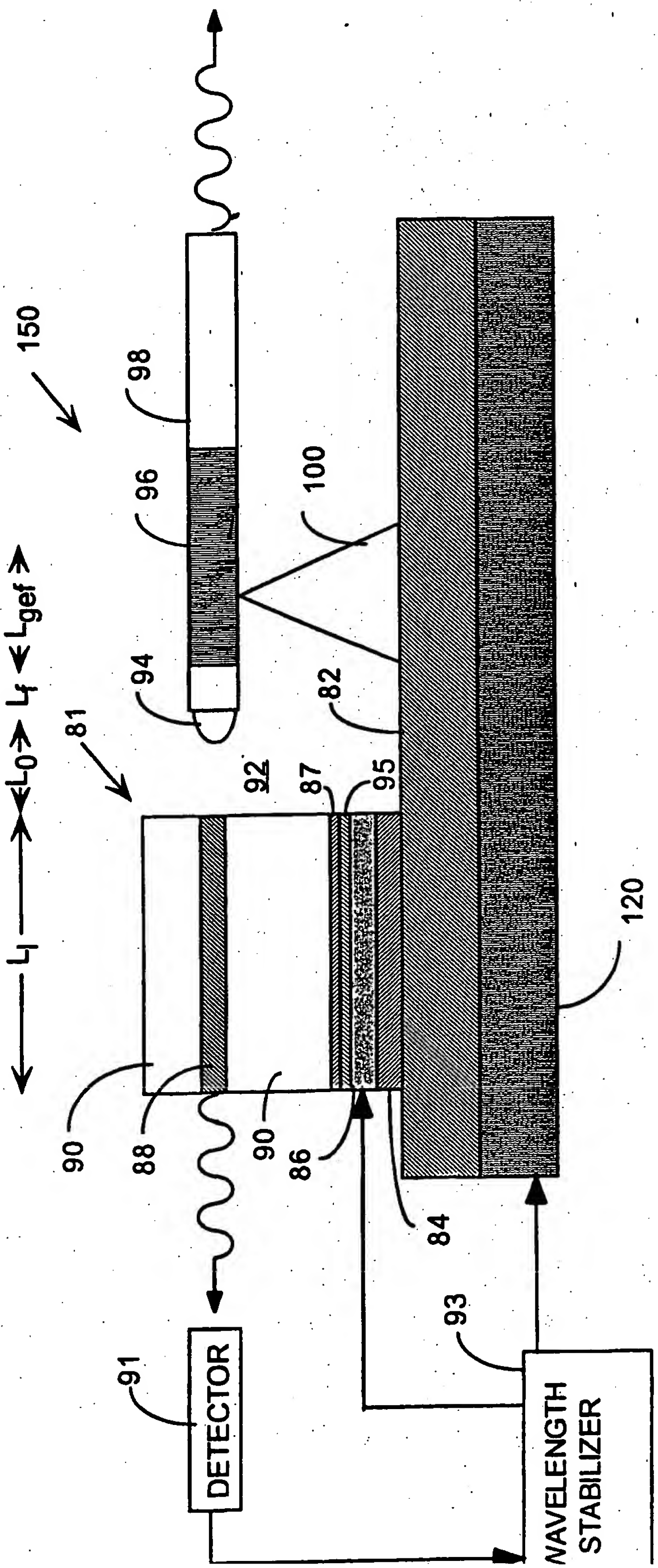
150
98
96
100
94
82
81
92
87
95
120
90
88
90
86
84
93
91
DETECTOR
WAVELENGTH STABILIZER

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL00/00401

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01S 3/00
US CL : 372/33
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 372/33, 32

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,914,972 A (SIALA et al.) 22 June 1999 (22.06.1999), see entire document.	1-33
A	US 5,870,417 A (VERDIELL et al.) 09 February 1999 (09.02.1999), see entire document.	1-33

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion f the international search
25 September 2000 (25.09.2000)

Date f mailing of the international search report
27 OCT 2000

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Form PCT/ISA/210 (second sheet) (July 1998)